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EXPERIMENTAL STRESS ANALYSIS ACTIVITIES IN  
SELECTED EUROPEAN LABORATORIES. PART 2

A. J. Durelli

Catholic University of America

Prepared for:

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Some of the comments made on the work conducted in the countries that have been visited, attempt to abstract characteristics. It is hoped that this kind of reporting may be useful, but it is obviously risky when practical considerations limit the number of selected places to be visited, and the allowable time to be spent in each of them. The reader should use judgement in the evaluation.

EXPERIMENTAL STRESS ANALYSIS ACTIVITIES

IN SELECTED EUROPEAN LABORATORIES

by

A. J. Durelli

Sponsored by

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April 1975

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This report is a continuation of the report published in August, 1968, under the same title. It summarizes the impressions received by the author during a trip through several countries in Europe, made from September to December, 1974. Several of the laboratories, institutes, universities, or government establishments visited, had already been visited in 1967 and 1968, which may permit the reader to follow the evolution of some of the work conducted in them. Several other of the places visited have been visited only once, for reasons of time (the second trip was much shorter than the first one), or for some other practical considerations. In general the reader will find advantageous to start with the first part.

Some of the comments made on the work conducted in the countries that have been visited, attempt to abstract characteristics. It is hoped that this kind of reporting may be useful, but it is obviously risky when practical considerations limit the number of selected places to be visited, and the allowable time to be spent in each of them. The reader should use judgment in the evaluation.

Papers Published Under Sponsorship of U. S. Army Research Office (Durham)

1. Durelli, A.J., and Ferrer, L., "New Methods to Determine Elastic Constants", Materials Research and Standards, Vol. 3, No. 12, pp. 988-991, Nov. 1963.
2. Durelli, A.J., The William M. Murray Lecture, 1965, "Visual Representation of the Kinematics of the Continuum", Experimental Mechanics, Vol. 6, No. 3, pp. 113-139, March 1966. Proceedings of Society of Experimental Stress Analysis, Vol. XXIII, No. 1, pp. 113-139. Proceedings of the 2nd SESA International Congress on Experimental Mechanics, 1966, pp. 1-27.
3. Durelli, A. J., Parks, V. J., and Mulzet, A., "On the Determination of the Sum of the Principal Stresses in Two-Dimensional Problems", Experimental Mechanics, Vol. 6, No. 9, pp. 19A-27A, September 1966.
4. Parks, V. J., and Durelli, A. J., "On the Definitions of Strain and Their Use in Large-Strain Analysis", Experimental Mechanics, Vol. 7, No. 6, pp. 279-280, June 1967.
5. Durelli, A. J., Parks, V. J., and Feng, H., "Evaluation of Grid Data to Determine Displacements and Strains", Journal of Strain Analysis, Vol. 2, No. 3, pp. 181-187, July 1967.
6. Durelli, A. J., Parks, V. J., and Feng, H., "Experimental Methods of Large Strain Analysis", International Journal of Non-Linear Mechanics, Vol. 2, pp. 387-404, 1967.
7. Durelli, A. J., Parks, V. J., and Ferrer, L., "Photography Without Lenses", Experimental Mechanics, Vol. 8, No. 3, pp. 142-144, March 1968.
8. Parks, V. J., and Durelli, A. J., "Natural Stress," International Journal of Non-Linear Mechanics, Vol. 4, pp. 7-16, March 1969.
9. Durelli, A. J., Parks, V. J., and Chen, L., "Stress and Finite Strain Analysis of a Circular Ring Under Diametral Compression," Proceedings of the Army Symposium on Solid Mechanics, Sept. 1968. Experimental Mechanics, Vol. 9, No. 5, pp. 210-214, May 1969.
10. Chiang, F. P., Parks, V. J. and Durelli, A. J., "Moire Fringe Interpolation and Multiplication by Fringe Shifting," Experimental Mechanics, Vol. 8, No. 12, pp. 554-560, December 1968.
11. Durelli, A. J., Parks, V. J. and Lopardo, V. J., "Natural Stress Used to Obtain Linear Elastic and Optical Properties of a Rubber Under Large Strain," Experimental Mechanics, Vol. 10, No. 6, pp. 240-244, June 1970.
12. Durelli, A. J., Chandrashekhara, K. and Parks, V. J., "In-plane Moire Strain Analysis of Bent Plates," International Journal of Solids and Structures, Vol. 6, pp. 1277-1285, September 1970.

13. Durelli, A. J., Parks, V. J. and Lopardo, V. J., "Stress and Finite Strain Around an Elliptical Hole in Finite Plates Subjected to Uniform Load," International Journal of Non-Linear Mechanics, Vol. 5, pp. 397-411, 1970.
14. Durelli, A. J., Chen, T. L. and Parks, V. J., "Velocity Fields in a Sphere Subjected to Large Deformations," Journal of Applied Mechanics, Vol. 41, No. 4, pp. 860-866, December 1974.
15. Chen, T. L. and Durelli, A. J., "Displacements and Finite-Strain Fields in a Hollow Sphere Subjected to Large Elastic Deformations," International Journal of Mechanical Sciences, Vol. 16, pp. 777-788, 1974.



Previous Technical Reports to the Office of Naval Research

1. A. J. Durelli, "Development of Experimental Stress Analysis Methods to Determine Stresses and Strains in Solid Propellant Grains" -- June 1962.  
Developments in the manufacturing of grain-propellant models are reported. Two methods are given: a) cementing routed layers and b) casting.
2. A. J. Durelli and V. J. Parks, "New Method to Determine Restrained Shrinkage Stresses in Propellant Grain Models" -- October 1962.  
The birefringence exhibited in the curing process of a partially restrained polyurethane rubber is used to determine the stresses associated with restrained shrinkage in models of solid propellant grains partially bonded to the case.
3. A. J. Durelli, "Recent Advances in the Application of Photoelasticity in the Missile Industry" -- October 1962.  
Two- and three-dimensional photoelastic analysis of grains loaded by pressure and by temperature are presented. Some applications to the optimization of fillet contours and to the redesign of case joints are also included.
4. A. J. Durelli and V. J. Parks, "Experimental Solution of Some Mixed Boundary Value Problems" -- April 1964.  
Means of applying known displacements and known stresses to the boundaries of models used in experimental stress analysis are given. The application of some of these methods to the analysis of stresses in the field of solid propellant grains is illustrated. The presence of the "pinching effect" is discussed.
5. A. J. Durelli, "Brief Review of the State of the Art and Expected Advance in Experimental Stress and Strain Analysis of Solid Propellant Grains" -- April 1964.  
A brief review is made of the state of the experimental stress and strain analysis of solid propellant grains. A discussion of the prospects for the next fifteen years is added.
6. A. J. Durelli, "Experimental Strain and Stress Analysis of Solid Propellant Rocket Motors" -- March 1965.  
A review is made of the experimental methods used to strain-analyze solid propellant rocket motor shells and grains when subjected to different loading conditions. Methods directed at the determination of strains in actual rockets are included.
7. L. Ferrer, V. J. Parks and A. J. Durelli, "An Experimental Method to Analyze Gravitational Stresses in Two-Dimensional Problems" -- October 1965.  
Photoelasticity and moire methods are used to solve two-dimensional problems in which gravity stresses are present.

8. A. J. Durelli, V. J. Parks and C. J. del Rio, "Stresses in a Square Slab Bonded on One Face to a Rigid Plate and Shrunk" -- November 1965.  
A square epoxy slab was bonded to a rigid plate on one of its faces in the process of curing. In the same process the photoelastic effects associated with a state of restrained shrinkage were "frozen in." Three dimensional photoelasticity was used in the analysis.
9. A. J. Durelli, V. J. Parks and C. J. del Rio, "Experimental Determination of Stresses and Displacements in Thick-Wall Cylinders of Complicated Shape" -- April 1966.  
Photoelasticity and moire are used to analyze a three-dimensional rocket shape with a star shaped core subjected to internal pressure.
10. V. J. Parks, A. J. Durelli and L. Ferrer, "Gravitational Stresses Determined Using Immersion Techniques" -- July 1966.  
The methods presented in Technical Report No. 7 above are extended to three dimensions. Immersion is used to increase response.
11. A. J. Durelli and V. J. Parks, "Experimental Stress Analysis of Loaded Boundaries in Two-Dimensional Second Boundary Value Problems" -- February 1967.  
The pinching effect that occurs in two-dimensional bonding problems, noted in Reports 2 and 4 above, is analyzed in some detail.
12. A. J. Durelli, V. J. Parks, H. C. Feng and F. Chiang, "Strains and Stresses in Matrices with Inserts" -- May 1967.
13. A. J. Durelli, V. J. Parks and S. Uribe, "Optimization of a Slot End Configuration in a Finite Plate Subjected to Uniformly Distributed Load" -- June 1967.  
Two-dimensional photoelasticity was used to study various elliptical ends to a slot, and determine which would give the lowest stress concentration for a load normal to the slot length.
14. A. J. Durelli, V. J. Parks and Han-Chow Lee, "Stresses in a Split Cylinder Bonded to a Case and Subjected to Restrained Shrinkage" -- January 1968.  
A three-dimensional photoelastic study that describes a method and shows results for the stresses on the free boundaries and at the bonded interface of a solid propellant rocket.
15. A. J. Durelli, "Experimental Stress Analysis Activities in Selected European Laboratories" -- August 1968.  
This report has been written following a trip conducted by the author through several European countries. A list is given of many of the laboratories doing important experimental stress analysis work and of the people interested in this kind of work. An attempt has been made to abstract the main characteristics of the methods used in some of the countries visited.

16. V. J. Parks, A. J. Durelli and L. Ferrer, "Constant Acceleration Stresses in a Composite Body" -- October 1968  
Use of the immersion analogy to determine gravitational stresses in two dimensional bodies made of materials with different properties.
17. A. J. Durelli, J. A. Clark and A. Kochev, "Experimental Analysis of High Frequency Stress Waves in a Ring" -- October 1968  
A method for the complete experimental determination of dynamic stress distributions in a ring is demonstrated. Photoelastic data is supplemented by measurements with a capacitance gage used as a dynamic lateral extensometer.
18. J. A. Clark and A. J. Durelli, "A Modified Method of Holographic Interferometry for Static and Dynamic Photoelasticity" -- April 1969  
A simplified absolute retardation approach to photoelastic analysis is described. Dynamic isopachics are presented.
19. J. A. Clark and A. J. Durelli, "Photoelastic Analysis of Flexural Waves in a Bar" -- May 1969  
A complete direct, full field optical determination of dynamic stress distribution is illustrated. The method is applied to the study of flexural waves propagating in a urethane rubber bar. Results are compared with approximate theories of flexural waves.
20. J. A. Clark and A. J. Durelli, "Optical Analysis of Vibrations in Continuous Media" -- June 1969  
Optical methods of vibration analysis are described which are independent of assumptions associated with theories of wave propagation. Methods are illustrated with studies of transverse waves in prestressed bars, snap load of bars and motion of a fluid surrounding a vibrating bar.
21. A. J. Parks, A. J. Durelli, K. Chandrashekhara and T. L. Chen, "Stress Distribution Around a Circular Bar, with Flat and Spherical Ends, Embedded in a Matrix in a Triaxial Stress Field" -- July 1969  
A three-dimensional photoelastic method to determine stresses in composite materials is applied to this basic shape. The analyses of models with different loads are combined to obtain stresses for the triaxial cases.
22. A. J. Durelli, V. J. Parks and L. Ferrer, "Stresses in Solid and Hollow Spheres Subjected to Gravity or to Normal Surface Traction" -- October 1969  
The method described in Report No. 10 above is applied to two specific problems. An approach is suggested to extend the solutions to a class of surface traction problems.
23. J. A. Clark and A. J. Durelli, "Separation of Additive and Subtractive Moire Patterns" -- December 1969  
A spatial filtering technique for adding and subtracting images of several gratings is described and employed to determine the whole field of Cartesian shears and rigid rotations.

24. R. J. Sanford and A. J. Durelli, "Interpretation of Fringes in Stress-Holo-Interferometry" -- July 1970.  
Errors associated with interpreting stress-holo-interferometry patterns as the superposition of isopachics (with half order fringe shifts) and isochromatics are analyzed theoretically and illustrated with computer generated holographic interference patterns.
25. J. A. Clark, A. J. Durelli and P. A. Laura, "On the Effect of Initial Stress on the Propagation of Flexural Waves in Elastic Rectangular Bars" -- December 1970.
26. A. J. Durelli and J. A. Clark, "Experimental Analysis of Stresses in a Buoy-Cable System Using a Birefringent Fluid" -- February 1971.  
An extension of the method of photoviscous analysis is presented which permits quantitative studies of strains associated with steady state vibrations of immersed structures. The method is applied in an investigation of one form of behavior of buoy-cable systems loaded by the action of surface waves.
27. A. J. Durelli and T. L. Chen, "Displacements and Finite-Strain Fields in a Sphere Subjected to Large Deformations" -- February 1972.  
Displacements and strains (ranging from 0.001 to 0.50) are determined in a polyurethane sphere subjected to several levels of diametral compression. A 500 lines-per-inch grating was embedded in a meridian plane of the sphere and moire effect produced with a non-deformed master. The maximum applied vertical displacement reduced the diameter of the sphere by 27 per cent.
28. A. J. Durelli and S. Machida, "Stresses and Strain in a Disk with Variable Modulus of Elasticity" -- March 1972.  
A transparent material with variable modulus of elasticity has been manufactured that exhibits good photoelastic properties and can also be strain analyzed by moire. The results obtained suggests that the stress distribution in the homogeneous disk. It also indicates that the strain fields in both cases are very different, but that it is possible, approximately, to obtain the stress field from the strain field using the value of E at every point, and Hooke's law.
29. A. J. Durelli and J. Buitrago, "State of Stress and Strain in a Rectangular Belt Pulled Over a Cylindrical Pulley" -- June 1972.  
Two and three-dimensional photoelasticity as well as electrical strain gages, dial gages and micrometers are used to determine the stress distribution in a belt-pulley system. Contact and tangential stress for various contact angles and friction coefficients are given.
30. T. L. Chen and A. J. Durelli, "Stress Field in a Sphere Subjected to Large Deformations" -- June 1972.  
Strain fields obtained in a sphere subjected to large diametral compressions from a previous paper were converted into stress fields using two approaches. First the concept of strain-energy function for an isotropic, elastic body was used. Then, the stress field was determined with the Hookean type natural stress-natural strain relation. The results so obtained were also compared.

31. A. J. Durelli, V. J. Parks and H. M. Hasseem, "Helices Under Load" -- July 1973.  
Previous solutions for the case of close coiled helical springs and for helices made of thin bars are extended. The complete solution is presented in graphs for the use of designers. The theoretical development is correlated with experiments.
32. T. L. Chen and A. J. Durelli, "Displacements and Finite Strain Fields in a Hollow Sphere Subjected to Large Elastic Deformations" -- September 1973.  
The same methods described in No. 27 were applied to a hollow sphere with an inner diameter one half the outer diameter. The hollow sphere was loaded up to a strain of 30 per cent on the meridian plane and a reduction of the diameter by 20 per cent.
33. A. J. Durelli, H. M. Hasseem and V. J. Parks, "New Experimental Method in Three-Dimensional Elastostatics" -- December 1973.  
A new material is reported which is unique among three-dimensional stress-freezing materials, in that, in its heated (or rubbery) state it has a Poisson's ratio which is appreciably lower than 0.5. For a loaded model, made of this material, the unique property allows the direct determination of stresses from strain measurements taken at interior points in the model.
34. J. Wolak and V. J. Parks, "Evaluation of Large Strains in Industrial Applications" -- April 1974.  
It was shown that Mohr's circle permits the transformation of strain from one axis of reference to another, irrespective of the magnitude of the strain, and leads to the evaluation of the principal strain components from the measurement of direct strain in three directions.

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BRITISH STRESS ANALYSIS LABORATORIES

University of Surrey  
Surrey, England

Royal Aircraft Establishment  
Structures Department  
Farnborough, Hampshire  
Hants, England

Rocket Propulsion Establishment  
Westcot, NRN  
Aylesbury  
Bucks, England

University of Oxford  
Oxford, England  
Ph: 0865-58293

University of Cambridge  
University Engineering Department  
Cambridge CB21PZ, England

National Engineering Laboratories  
East Kilbride  
Glasgow, United Kingdom

Naval Construction Research Establishment  
St. Leonard's Hill  
Dunfermline, Fife  
Scotland, United Kingdom



## UNIVERSITY OF SURREY

Scientists particularly interested in experimental stress analysis methods are: I. M. Allison, P. Nurse and D. E. Stone.

The University of Surrey is relatively new. It developed from an old technical school and benefited from generous budgets aimed at making it grow. It has about 3,000 students in science, engineering and some humanistic subjects like linguistics.

Allison has one of the most active experimental stress analysis laboratories in England and one of the three or four that work intensively in three-dimensional photoelasticity. The laboratory is supported financially to an appreciable extent through contracts with industry, but in particular through contracts with government agencies. Of particular interest at present are studies dealing with bolted connections in ships, stresses in a prosthesis for a mouth bone, and inspection of composites using ultrasonics. The most spectacular project is the design and construction of an automated polariscope at a cost of approximately \$100,000. Several details of the instrument have already been published in the open literature<sup>[1]</sup>. It is claimed that the location of points in the model is given with a precision of about  $5 \times 10^{-4}$  in., the isoclinic angles with about  $0.3^\circ$ , the isochromatic orders with about  $2 \times 10^{-2}$  fringe. The time necessary to obtain the individual stresses is three minutes plus 15 seconds per point. The instrument seems more practical, easier to use and to manufacture than some of the other automatic polariscopes previously developed. The philosophical question still stands: is it worthy?

---

[1] Nurse, P. and Allison, I. M., "Automatic Acquisition of Photoelastic Data," J.B.C.S.A. Conference, pp. 19-23, 1972.

#### ROYAL AIRCRAFT ESTABLISHMENT

Scientists particularly interested in experimental stress analysis methods are: Mansfield, Mullins and D. E. Stone.

Awareness of the problems and interest in methodology is keen, but it does not seem that experimental stress analysis work of importance is conducted now at the establishment. V. M. Hickson has retired some years ago. It was not possible to visit any of the laboratories.

#### ROCKET PROPULSION ESTABLISHMENT

Scientists particularly interested in experimental stress analysis methods are: H. J. Buswell, Lorelay and G. S. Young.

AD 86930  
There is great concern with the manufacturing of a gage that would permit the determination of stresses in actual solid propellant grains, for rockets. The idea being developed at present consists in embedding in the grain a small, about 3 mm. diameter, 15 mm. long, epoxy bar. One face of the bar is flush with a free surface, the other is mirrored. A central hole about 1 mm in diameter goes all along the axis of the bar. It has been shown in a paper previously published in Experimental Mechanics<sup>[1]</sup> that, provided the insert is much more rigid than the propellant, the photoelastic response of such an insert would correspond to the stress in the propellant. The idea has great potentiality and Buswell claims good correlation between measured birefringence and a known state of stress. The techniques used to measure birefringence in such small specimen with very small holes, and a long light path, are difficult, and should be precise. Fringes around the edge of the hole are not clear and determinations have to be made inside the field. Change in color associated with rotation of analyzer is used to determine fractional fringe order, but the need for this unusual method is not clear.

---

[1] Buswell, H. J., Moore, D. R. and Owens, A., "The Use of a High modulus inclusion Gage in Nonlinear Viscoelastic Materials," Experimental Mechanics, Vol. 14, No. 7, pp. 274-280, July 1974.

#### UNIVERSITY OF OXFORD

One of the scientists particularly interested in experimental stress analysis methods is C. Ruiz.

The university has about 12,000 students. About 600 of these are in engineering (450 undergraduates and 150 graduates). Research projects and consulting with industry depend essentially on the professor's interest. It seems obvious that the main concern of the experimental work at Oxford is the education of the student. A large number of devices have been designed and built for the student to conduct structural tests by himself.

An attempt is being made at the study of crack propagation in polycarbonate plates, as models of steel plates. A very interesting manufacturing technique used here is the preparation of epoxy tubes by centrifugation. It is claimed that no residual effects are left, and the boundaries are clear for photoelastic observation.

## UNIVERSITY OF CAMBRIDGE

One of the scientists particularly interested in experimental stress analysis methods is K. Pascoe.

X-ray applications to soil mechanics are important. Either small lead spheres are embedded in the soil and the x-ray follows their motion, or advantage is taken of the change in density in some soils like sand, when they slide. Studies are conducted on uniaxial and biaxial creep of metals at high temperature, and on low cycle fatigue. Fatigue determinations are also conducted on glass-fiber-reinforced polyester plates with direct application in ship manufacturing. The buckling of shells is simulated using silicone rubbers.

Two outstanding characteristics of the experimental work are the great concern with the education of the students and the deliberate purpose of being useful to industry. Little pure research is seen. And the number of devices to be used by students to make experiments by themselves in structural analysis, heat treatment of metals, properties of materials, etc. is enormous. Nothing similar can be seen in the U.S.A.

A visit to Cambridge should be compulsory to every university man, as the opportunity to have a unique experience in his life. Where else could the university man see such a mixture of tradition, beauty, intellectual life and respect for common values?

The objective of a university, and the relation between science, teaching and research are very well expressed in the official description of the engineering activities at Cambridge, of which the following excerpts are taken:

"Engineering applies to human needs the knowledge that science has given us of natural phenomena...Engineering uses science, but involves values outside science.

"...engineer' is...a member of a profession...who has recognised graduate qualifications, and whose work it is to devise and plan machines, devices and structures, and to oversee their construction and operation.

"Much of engineering is strongly dependent on physics... However... the typical engineering design problem does not have a unique solution; there are usually several alternative possibilities, and judgement is required to assess their relative merits... Compared with the scientist, the engineer is much more concerned with the impact of his work on other people...

"...to understand scientific principles... an essential starting point... is a reasonable competence in mathematics... though... a creative and imaginative mind is more important.

"University courses in engineering deal mainly with scientific principles and their applications. It is recognised in Britain that the graduate leaving the university is not yet an engineer...

"...1795... the Professor of Natural Philosophy... gave a series of lectures intended...

'to excite the attention of persons already acquainted with the principles of mathematics... to real practice... to enlarge their sphere of amusement and instruction, and to promote the improvement and progress of the Arts.'

"The lectures were illustrated by experiments and working models, and contemporary accounts describe them as entertaining and very popular... the proportion of undergraduates studying engineering has been almost constant for more than fifty years, at about one in ten. The Department has also become an important centre of research...

"The courses in engineering at Cambridge have some special features... First, it is clearly acknowledged that the purpose of the course... is to educate the students, rather than to train them to do a particular job. This means that the courses are designed to develop the students' intellectual abilities... Thus the emphasis is placed firmly on the understanding of a relatively small number of basic scientific principles and the solution of engineering problems by the application of these principles. Very little time is spent in teaching facts... because such knowledge would rapidly become out of date.

"... all the students take a general course, covering all the main engineering subjects, for the first two years... The Cambridge engineering student thus defers his choice of specialism until the end of his second year, and then chooses between different scientific disciplines rather than between the traditional branches of engineering... the broad background of the Cambridge engineer, and the confidence that it gives him in tackling a wide range of problems, make him extremely useful in industry...

"The staff of the Engineering Department... are also engaged in research, together with about 150 research students... in close collaboration with industry, or with government research establishments. This research informs their teaching."

## NATIONAL ENGINEERING LABORATORIES

One of the scientist particularly interested in experimental stress analysis methods is J. R. Dixon.

Holography is used to measure displacements perpendicular to the surface of loaded bodies, and to determine the size and position of small particles in fluids moving in a duct. Photoelasticity is little used at present. The last application dealt with studies of stress distributions at the intersection of several tubes, as at the joints of the structural components of the rigs to be used to drill oil wells in the North Sea.

## NAVAL CONSTRUCTION RESEARCH ESTABLISHMENT

Scientists particularly interested in experimental stress analysis methods are: J. M. Cargill, P. R. Christopher and S. Kendrick.

The closest correspondence in the U.S.A. to this establishment is the Naval Ship Research and Development Center at Carderock, Maryland, the old David Taylor Model Basin. Nearby five thousand people work in stockyards.

Photoelasticity is no more used. When photoelasticity work is required it is contracted outside the establishment. It is felt that finite element methods are less expensive, require less training of the operator, and give answers in shorter time. An original and important contribution to moire techniques is the use of "replicas" to reproduce gratings, as dense as 1,000 lpi. Two problems are of particular concern: the use of moire to determine strains associated with weldings, and the measurement of the depth of cracks.

Numerous tests are conducted on submarine models (as large as 1/5 full scale) when subjected to explosions. Electric strain gages are mostly used as sensors. The buckling of stiffeners is of particular interest.



COMMENTS ON THE EXPERIMENTAL STRESS ANALYSIS WORK CONDUCTED IN THE VISITED  
PLACES IN ENGLAND AND SCOTLAND

It seems that in the last seven years developments in experimental stress analysis methods and applications have slowed down in England and Scotland. Several establishments have ceased to be interested in photoelasticity and in brittle coatings. In two or three places however, activity in three-dimensional photoelasticity is as intense as or more intense than in any other country. It is still here where it can be found the greatest concern to have students conduct experiments with their own hands and it is here where university laboratories show the greatest interest in the solution of problems of importance to industry.

FRENCH STRESS ANALYSIS LABORATORIES

Institut National des Sciences Appliquees (INSA)  
20 Av. Albert Einstein  
69621 Villeurbanne, France

Laboratoire National des Ponts et Chaussees  
59 Boulevard Lefebvre  
Paris XV<sup>e</sup>, France

Universite de Poitiers, Faculte des Sciences, Laboratoire de Mecanique  
86004 Poitiers, France

## INSTITUT NATIONAL DES SCIENCES APPLIQUEES (INSA)

Scientists particularly interested in experimental stress analysis methods are: Bahuaud, C. Bremond, J. Cubaud, Duhau, Ewins, Professor Godet, J. F. Jullien, Lafont, M. Lalanne, Progri, P. Trompette.

Located in a Lyon's suburb, sharing the campus with some schools of the University of Lyon, the INSA begins to fulfill one of the objectives for which it was created. As an engineering school with 3,000 students it has few graduate courses, but a strong effort has been made in some of the departments to obtain financial support from industry and government agencies. Two groups are particularly outstanding in that respect, the experimental stress analysis section of the Civil Engineering School, and the sections of the Mechanical Engineering School, dealing with the mechanics of contact, and the dynamics and damping of structures.

Contracts in experimental stress analysis deal mainly with structures containing nuclear reactors, with intersections of highways and with several phases of Lyon's subway construction. Two and three-dimensional photoelasticity are used for the measurements in structural models, which include the soil below the foundation. This is probably the most original contribution of these laboratories: materials have been developed that permit the modelling of soils with different elastic properties. With the exception of the ISMES in Bergamo, the INSA is probably the only laboratory where the structure is modelled in its entirety, including the soil. The models of the nuclear reactor structures are made of epoxy, cast to final size and probably the most complicated ever built. J. F. Jullien is in charge of these activities.

The largest part of contracts in the Mechanical Engineering School deal with problems in the field of tribology (friction, wear and lubrication). The financial support is of the order of \$200,000 a year. Professor Godet is head of this section which has about 30 people. One of the problems of interest is

the behavior of lubricating fluids pushed between a flat plate, for instance, and a rotating disk or wheel. Depending on speed and viscosity the fluid may drop back from the interface. There seem to be few experimental methods to better understand this problem. In the group is C. Bremond conducting a thesis on the determination of the state of strain at the interface between a flat semi-infinite plate and a disk resting on it. It is essentially Hertz problem, but without the simplifying assumption of no shear at the interface. The problem is being attacked making a rubber model of the flat plate with a cross-grating in the central plane. The solution shows originality. The grating is prepared on a milling machine with density of two lines per millimeter and is printed on the surface of the rubber using resifax photosensitive solution. The two halves are not cemented together but just adhere to each other and stay that way without a need of any extra force. It is planned to photograph the grating when the plate is subjected to successively larger amounts of load applied by a metal disk.

After the method is under control it will permit a study of contact stresses for different conditions at the interface, for instance, different frictional forces. It may be possible also to study those conditions not only for vertical loads, but for combinations of vertical loads and tangential loads or moments applied to the disk. Progre is approaching the solution of similar problems using photoelasticity.

The group of Lalanne, Trompette and Ewins has also outside financial support, this one from a government agency supporting research of interest to the defense department. They have studied turbine blades and have determined stresses, modes and frequencies using finite-element methods. So far the blades have been considered as plates, neglecting the double curvature. They are also working on the damping of the turbine blades using ceramic layers.

Bahuaud is interested in machine design problems, and has contributed to the analysis of belville springs. Research has been conducted on plasticity, fatigue and buckling problems. Of particular interest is the determination of contact pressure at the face of a hip prosthesis, using embedded strain gages.

## LABORATOIRE NATIONAL DES PONTS ET CHAUSSEES

Scientists particularly interested in experimental stress analysis methods are: A. Bonnet, Caussignac, J. L. Salhi, C. Santini.

Work is being conducted, apparently not successfully yet, to automatize the evaluation and differentiation of moire records. Polariscope designed by Robert is used and found good for the determination of maximum shears, but not satisfactory for the determination of isoclinics. They use a mixture of gelatin and glycerine to determine strains associated with gravitation. It is said that polyurethane rubbers are difficult to obtain in France and the manufacturing of the gelatine-glycerine mixture is well under control.

The deflections of thin plates are obtained using holography, on plexiglass models. To decrease the number of fringes only a few grams load is used. The information should be fed into a computer to be differentiated twice. No evidence of this working properly could be seen.

It is not possible to avoid the feeling that the level of the research conducted by Mesnager, Tesar and Dantu has appreciably decreased. There seems to be little concern in applying experimental stress analysis techniques to the teaching of students, and little concern with research. The main concentration seems to be in the solution of applied problems submitted by the interested government agencies. The lack of familiarity with foreign literature is noticeable.

UNIVERSITE DE POITIERS, FACULTE DES SCIENCES, LABORATOIRE DE MECANIQUE

Scientists particularly interested in experimental stress analysis methods are: J. Garnault, Professor A. Lagarde, G. Martin, J. M. Bourot, M. Coutanceau, J. Derouet, M. Fortune and T. Gamby.

One of the main interests of Professor Lagarde continues to be the development of dynamic photoelasticity methods, following the same approaches he used several years ago, which require the recording of light intensity to determine birefringence and displacements. Among the new projects the following seem particularly promising: 1) use of glass fibers to transmit birefringence from a plate, or a photoelastic coating, to a recorder. The amount of light attenuated this way may be appreciable, but it does not seem clear yet how much it is; 2) recording of isochromatics of order  $n/4$ ; and 3) a very simple set-up, that uses a standard slide projector, to project 500 lp $\ddot{a}$  gratings on the surface of plates and so to illustrate by moire the deflection of the deformed plates.

COMMENTS ON THE EXPERIMENTAL STRESS ANALYSIS WORK CONDUCTED IN THE VISITED  
PLACES IN FRANCE

Great concern with the development of very elaborated equipment and with the automatizing of the processing of information. Strangely enough this takes place when there are few instances of application of the experimental stress analysis methods. The philosophy seems to be that if equipment were faster and more automatic, more work will be conducted. The fact may be that if equipment were easier to use and less expensive, more work would be conducted.

New efforts at INSA to work on problems of technological interest.



BELGIAN STRESS ANALYSIS LABORATORIES

Universite de Louvain. Institut des Constructions  
Park d'Arenberg  
Heveslee, Louvain, Belgium

Universite de Louvain-la-Neuve  
I348 Louvain-la-Neuve  
(R.R. Station: Ottignies)  
Belgium

Universite Libre de Bruxelles  
Laboratoire d'Analyse des Contraintes  
87 Av. A. Buyl  
Bruxelles 5, Belgium

Scientists particularly interested in experimental stress analysis methods are: R. Snoeys and Professor Van Laethem.

This is the Flemish speaking university born of the split of the old Louvain into two universities, a Flemish speaking and a francophone. They will eventually be of about equal size, about 15,000 students each.

Professor Van Laethem is in charge of laboratories dealing with experimental mechanics problems. He is particularly interested in buckling of shells and has tested by vacuum half of an ellipsoidal shell, with axes of 2 and 1.5 meters, and thickness of 2.5 mm. Finite-elements and finite-differences analysis were also conducted and results compared to experimentally obtained results. It is believed that the comparison is satisfactory, but several experimental conditions raise serious questions: the geometry of the polyester model is far from ideal and the influence of departures from ideal geometry, on buckling, is not completely understood; the boundary conditions at the interface between the half ellipsoid and the plane on which it rests is not well known. Results obtained using finite-differences agree well with those obtained using finite-elements, but finite differences in this case was found to be less practical than finite-elements. Nine elements per quadrant were found sufficient.

Another problem studied at present is the determination of the natural frequencies of slabs made of a complicated framework of tubes. Also studied as subject of a doctor's thesis is the deformation of folded plates made of concrete reinforced with 4 cm. long and 0.3 mm. thick steel fibers. Some of the folded plates have been prestressed: concrete and steel fibers is a composite material of typical characteristics.

The old University of Louvain, which is the one that will be all Flemish speaking, is located in one of the most beautiful parts of the town and has five centuries of tradition. It is worth mentioning that the Rector is elected

by the faculty and so are the deans. The deans are elected for a period of three years and can be reelected only once and for one more year. After the fourth year they have to retire to become professors again. As all the universities in Belgium, the Catholic University of Louvain is 95% supported financially by the state. This means, of course, some state control which until now has been rather reasonable, but worries some of the members of the faculty. It is accepted, however, that without the financial support of the state the Catholic University of Louvain would not exist today.

## UNIVERSITE DE LOUVAIN-LA-NEUVE

Scientists particularly interested in experimental stress analysis methods are: Professor F. Buckens and Professor Lousberg, the first one in the Department of Applied Mechanics and the second in the Department of Civil Engineering.

The new campus has about 900 hectares. About 2,000 students are attending classes already and most of them living at the new university. About 1,500 more are still at the old campus. It is expected that when finished the university will have about 15,000 students.

At present one of Professor Buckens' interests is the design and study of air supported bearings. Neat demonstrations have been prepared illustrating the principle for educational purposes.

There is great interest in studies related to the enlargement of canals. This means of transportation is popular and very important economically in Belgium, but most canals have been built many years ago and there is an advantage in using larger or wider boats. For that purpose a testing canal has been built in the laboratories to determine all the flow characteristics of different design alternatives. The material testing laboratories still conduct appreciable amount of tests for the government, for instance for the acceptance of pavement specifications. These routine testings do not seem to interfere with teaching or research and the faculty claims that they are a good source of income.

Professor Lousberg is studying at present the influence of irregularities in the shape of aggregates found in Belgium, on the properties of pavements manufactured with those aggregates.

UNIVERSITE LIBRE DE BRUXELLES

Scientists particularly interested in experimental stress analysis methods are: J. Ebbeni, Professor J. Kestens, M. Vandaele and Professor R. Van Geen.

At present greatest concentration of interest seems to be on holography and on a few problems dealing with moire. Two students are trying to determine second order effects on the refraction phenomena in crystals using holography. Moire is applied to the surface of notched plates to determine the propagation of plastic zones and compare the results with those obtained using finite-elements, which do not seem to follow the physical phenomenon. Moire is also used to study strains in some asphalt specimens, after covering them with a latex coating. In the holograms of photoelastic materials an attempt is being made to eliminate the isochromatics and keep only the isopachics.

Professor Van Geen has been appointed rector of the new Flemish speaking University of Brussels. His contribution to the laboratory work has appreciably decreased.

## COMMENTS ON THE EXPERIMENTAL WORK CONDUCTED IN THE VISITED PLACES IN BELGIUM

Following recent decisions on national languages in Belgium, both the University of Brussels and the University of Louvain will split. Each of them will become two universities, one francophone and the other Flemish speaking. The University of Louvain has already started building the new dormitories, laboratories and offices at Louvain-la-Neuve near Ottignies, about half an hour from Brussels and not too far from the seat of the old Louvain. It is expected that each of the Louvain universities will have about 15,000 students. So far priority in moving has been given to schools in engineering and architecture.

In comparison with American counterparts the financial ease of Belgium universities is obvious.

In both Louvains, the old one and the new one there is a great deal of interest in developing experimental methods, but it seems that the main concern is not the solution of scientific or technological problems, but the use of these methods as a help in the teaching of engineering subjects.

It should be said also that in Louvain as in most European countries experimentalists feel that the amount of work has increased rather than decreased as a consequence of the competition from finite-elements methods, because many people lack confidence in the solutions obtained with the finite-elements and require experimental verification of those results. This is certainly not, at least to that extent, the situation in the United States.

DUTCH STRESS ANALYSIS LABORATORIES

National Aerospace Laboratory (N.L.R.)  
Northeast Polder, Holland

Technische Hoge School Delft. Lab. Voor Technische Mechanica  
Mekelweg 2  
Delft, Netherlands

# NATIONAL AEROSPACE LABORATORY (N.L.R.)

Scientists particularly interested in experimental stress analysis methods are: G. Bartelds, Av. de Koning and P. J. Sevenhuysen.

This laboratory is an independent foundation created in 1919 with the participation of Folke, KLM, the Dutch Air Force, and the ministries of Finance, Economics and Public Works. About 600 people work in the laboratory. Fifty percent of the work is done on contracts, for industry. Only 200 people work at Polder, the rest being still located in Amsterdam

Dr. G. Bartelds is head of the Structures Research Department. Av. de Koning and P. J. Sevenhuysen are particularly interested in experimental methods. Concentration is applied to the study of plasticity in aluminum alloys, some of which exhibit anisotropy. Measurements are taken mainly using electrical resistance strain gages, but moire methods are being developed. Rather than to follow more or less standard procedures, an attempt is made at automatizing the evaluation of the data. As most of the automatizing projects carried on for photoelasticity and moire, this one is a point-per-point method. It is not obvious that it will be more practical than the conventional whole-field methods. It does develop however, the ingenuity of the researcher. The method consists essentially in the determination of strains by measuring changes in the angle of diffraction of gratings. A laser is used as a source, and an especially built photo-cell targets the spot of light.



Scientists particularly interested in problems of continua and experimental mechanics are: Professors J. Besseling, W. T. Koiter, P. Meijers and A. D. Pater.

An important contribution is Meijers' work on multiperforated plates. He determined stress concentrations and "effective" moduli for a large variety of perforation patterns<sup>[1]</sup>.

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[1] Meijers, P., Doubly-Periodic Stress Distributions in Perforated Plates,  
December, 1967.

COMMENTS ON THE EXPERIMENTAL STRESS ANALYSIS WORK CONDUCTED IN THE VISITED  
PLACES IN HOLLAND

There is today a great interest in Holland on plasticity and creep. The approaches followed to solve problems of this kind are mainly theoretical. The experimental work is not very extensive and is directed mainly at verifying theoretical solutions. Experimental strain analysis methods are used mainly for educational purposes. It does not seem that scientists are very familiar with three-dimensional photoelasticity nor with moire with the exception of the method applied to the study of bent plates, as introduced by Lichtenberg.

GERMAN STRESS ANALYSIS LABORATORIES

Deutsche Forschungs und Versuchsanstalt für Luft und Raumfahrt (D.F.V.L.R.).  
Institut für Flugzeugbau  
Braunschweig, Germany

Technische Hochschule Clausthal. Fritz-Suchting-Institut für Maschinenwesen  
Robert-Koch Strasse 4  
3392 Clausthal-Zellerfeld 1, Germany

Technische Universität Braunschweig  
Braunschweig, Germany

Volkswagen, A. G.  
Wolfsburg, West Germany

DEUTSCHE FORSCHUNGS UND VERSUCHSANSTALT FÜR LUFT UND RAUMFAHRT (D.F.V.L.R.).  
INSTITUT FÜR FLUGZEUGBAU

Scientists particularly interested in experimental stress analysis methods are: B. Geier, Kharadi, Professor W. Thielemann and R. Zimmermann.

Studies are being conducted to determine the state of strain in very thin straight mylar cylinders subjected to axial loading, before the cylinder buckles. An attempt is being made to use holography for this purpose. Holograms have previously been obtained at Dornier from a large number of pressure vessels made of glass fiber reinforced epoxy. The shape of these vessels is like a sphere cut at the poles by two parallel planes. The final objective is to develop a non-destructive method to verify whether any weakness is present in any individual vessel. It has been found that the method is too sensitive, and it is sometimes difficult to establish the fringe order.

Scientists particularly interested in experimental stress analysis methods are: J. Barth, Boll, B. Jain, Professor A. Kuske and H. Lorenz.

Professor Kuske has in Clausthal one of the largest (about 10 people) and most productive teams in experimental stress analysis. It has developed very fast since the days, about seven years ago, when it started. Most of these people are advanced students working for the doctor's degree, some are foreigners (one Indian, one Greek, one Turk, one Czech, etc.), the others are German. Unusual is the interest that Kuske has managed to develop in them on experimental stress analysis methods, in particular, photoelasticity, at a time when almost everywhere else in the world there is a decrease in the interest on experimental methods. It is also remarkable the amount of work that he has now for industry. Most of this work is of contractual or private consulting nature and independent of the work conducted with his students. Particular mention should be made of several projects on dynamic photoelasticity which have been for many years one of the main interests of Professor Kuske. To that he has added now the photoelastic studies using plastics of stresses produced in the welding process. Although several methods are used, the lack of interest in moire is surprising.

A great effort is given to the simulation of welding stresses using polycarbonate models. Two sheets are welded by heating the joint with a standard heater for hot air (similar to heaters used to dry women's hair). When observed in a polariscope, patterns (extremely beautiful) are produced, which mostly disappear when the models are cut. It is claimed that a correlation exists with the presently available information on welding stresses in steel. The method would permit the study of the influence of discontinuities, shapes, etc., on welding stresses. In the Soviet Union similar studies are also conducted at present. Obviously the potentiality of the method is great, but no systematic study of the mechanical and optical properties of the material used, as

function of temperature and time, has been conducted yet. These studies should be previous to any conclusion.

Continuing traditional studies in dynamic photoelasticity emphasis is put on the influence of excentricity of impact on failure. Studies are also conducted to determine contact pressures in dies.

A great interest exists at present in photoplasticity. Epoxy without hardener, or with little hardener, is used, as model material. It is claimed that it acts as a Newton liquid, and after 5 seconds there is no more change in response. The material is very sensitive to changes in temperature. It is not clear whether the problem solved is a problem in plasticity, or a problem in lineal viscoelasticity.

A spark camera is being developed of the Schardin-Cranz type, but using laser as light source. The exposure time will be of the order of 20 nano seconds.

Professor Kuske has just published a book on photoelasticity with Professor Robertson from Scotland<sup>[1]</sup>.

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[1] Kuske, A. and Robertson, G., Photoelastic Stress Analysis, John Wiley & Sons, 1974.

TECHNISCHE UNIVERSITÄT BRAUNSCHWEIG

Scientists particularly interested in experimental stress analysis methods are: F. H. Hecker, Professors R. Ritter and W. Thielemann.

An attempt is being made at producing moire from plates subjected to impact, by projecting both the master and the deformed grating, using two half mirrors. So far contrast has not been satisfactory. The density of the projected gratings is about 12 lines per inch.

VOLKSWAGEN, A. G.

Scientists particularly interested in experimental stress analysis methods are: A. Happe, H. J. Koelbel and S. Uthe.

Dr. Koelbel is a physicist, Uthe is a mechanical engineer inclined to the solution of practical problems and Happe has a background in optics and his main interest is holography. About 25 problems a year are brought to the attention of the laboratory, more than half in photoelasticity and the rest in brittle coatings and other methods. The main characteristic of these problems is the speed expected for the answers. The problems are brought to the laboratory by a designer or a production engineer and the answers are not expected to be very rigorous or precise. As a consequence the approach followed in the solution of problems are solved, or from the approach followed when in general problems are solved in the framework of universities.

Studies were conducted to determine the stress distribution in wheels subjected to lateral impact. American "Stresscoat" was mainly used for the determinations. Sometimes Vishay's product is preferred because of the lack of fumes. The old German brittle coating is not manufactured anymore. The best position for a hole in the wheel was selected fast using this method between several alternatives. Photoelastic models are sometimes machined but frequently cast to final shape. The resin used is araldite B.

Particularly worth mentioning is the measurement of deflections associated with vibrations, using holography. The holographic equipment has been ingeniously designed and made portable. It is used to measure vibrations of car side panels, but it can even be used under the car to measure vibrations of the body bottom. Double exposure photographs give good sharp fringes, and permitted some redesigns to decrease the noise level. The problem of zero order fringe determination in the patterns, however, has not been solved. Using these holograms it could be



decided whether to reinforce doors to decrease the noise, or to dampen them, and in this case what kind of damping material to use.

Epoxy models have been used to study thermal stresses in brakes. Strain gage results have been compared to those obtained from finite element analysis.

TURKISH STRESS ANALYSIS LABORATORIES

Middle East Technical University  
Ankara, Turkey

#### MIDDLE EAST TECHNICAL UNIVERSITY

Scientists particularly interested in experimental stress analysis methods are: Z. Aktas, E. Atimtay, M. B. Civilek, T. Erdogan, Professor M. O. Kiciman and S. T. Wasti.

The university has 8,000 students in a new, very large campus (several thousand acres) a few miles from Ankara. Some 15 million trees were planted in the last 15 years making the campus and the dozens of buildings very attractive. All teaching is in English. Most students are Turks.

Material Testing Laboratories are well equipped: Erdogan is interested in the study of concrete subjected to fatigue, using the "brazilian" test specimen. There is interest also in the study of contact problems. As it is common in new universities in countries not industrialized, in spite the good facilities and the faculty capabilities research programs have great difficulty in getting off the ground.

## GENERAL REMARKS APPLICABLE IN PARTICULAR TO EXPERIMENTAL STRESS ANALYSIS ACTIVITIES

### 1. On Finite-element Methods

Concern on the relative position of experiments and finite-elements methods is paramount in all of the laboratories visited. From observations in the United States and in Europe it seems that: a) for two-dimensional problems, with a few exceptions, finite-elements methods seem to have displaced almost completely photoelasticity; b) for three-dimensional problems with rotational symmetry there is more competition, but finite-elements methods seem well suited; c) for three-dimensional problems with non-rotational symmetry in general photoelasticity does a faster and less expensive job; d) for time-dependent problems there is less competition, and so far finite-elements methods do not seem to have developed sufficient confidence in the investigator, and particularly in the designer and e) some times in the United States, and frequently in Europe, the finite-elements solution is available, but it is not trusted and independent experimental verification is desired. In Europe it is claimed that as a consequence photoelasticians have now more work than before.

### 2. On Education of Students

Undergraduate students in the classic universities like Cambridge and Oxford are helped and "educated" individually by tutors. Some of this is still seen in a few of American universities, but the pressure of large numbers has appreciably reduced the personal contact between student and teacher. In Continental and South American universities the personal guidance of the undergraduate has practically disappeared.

At the graduate level in European universities, there are almost no organized courses required from the students. Particularly in France the student is frequently left alone to pursue his studies, conduct his research and write his thesis. At the other extreme, in the United States the graduate student is fre-

quently guided in his research work and it is required from him that he take and pass successfully a long series of courses.

#### ACKNOWLEDGMENTS

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